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Citation for final published version:

Sani Hassan, Abubakar, Cipcigan, Liana Mirela ORCID: https://orcid.org/0000-0002-5015-3334 and Jenkins, Nicholas ORCID: https://orcid.org/0000-0003-3082-6260 2017. Optimal battery storage operation for PV systems with tariff incentives. Applied Energy 203 , pp. 422-441. 10.1016/j.apenergy.2017.06.043 file

Publishers page: http://dx.doi.org/10.1016/j.apenergy.2017.06.043 <http://dx.doi.org/10.1016/j.apenergy.2017.06.043>

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Applied Energy 203 (2017) 422–441

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Optimal battery storage operation for PV systems with tariff incentives ☆

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HIGHLIGHTS

- PV – Battery system under FiT incentive is modelled to maximise revenue streams.
- Optimisation model is developed to optimise power flows in the PV-Battery system.
- Real residential PV and demand data is used to simulate the optimisation model.
- Sensitivity analysis on the impact of battery capacity on the model is carried out.
- Impact of unit cost on the adoption of battery storage for PV under FiT is studied.

ARTICLE INFO

Article history:
Received 8 March 2017
Received in revised form 9 June 2017
Accepted 11 June 2017

Keywords:
PV-battery systems
Feed in tariff
Optimisation
Battery storage

ABSTRACT

Many efforts are recently being dedicated to developing models that seek to provide insights into the techno-economic benefits of battery storage coupled to photovoltaic (PV) generation system. However, not all models consider the operation of the PV – battery storage system with a feed-in tariff (FiT) incentive, different electricity rates and battery storage unit cost. An electricity customer whose electricity demand is supplied by a grid connected PV generation system benefiting from a FiT incentive is simulated in this paper. The system is simulated with the PV modelled as an existing system and the PV modelled as a new system. For a better understanding of the existing PV system with battery storage operation, an optimisation problem was formulated which resulted in a mixed integer linear programming (MILP) problem. The optimisation model was developed to solve the MILP problem and to analyse the benefits considering different electricity tariffs and battery storage in maximising FiT revenue streams for the existing PV generating system. Real data from a typical residential solar PV owner is used to study the benefit of the battery storage system using half-hourly dataset for a complete year. A sensitivity analysis of the MILP optimisation model was simulated to evaluate the impact of battery storage capacity (kWh) on the objective function. In the second case study, the electricity demand data, solar irradiance, tariff and battery unit cost were used to analyse the effect of battery storage unit cost on the adoption of electricity storage in maximising FiT revenue. In this case, the PV is simulated as a new system using Distributed Energy Resources Customer Adoption Model (DER-CAM) software tool while modifying the optimisation formulation to include the PV onsite generation and export tariff incentive. The results provide insights on the benefit of battery storage for existing and new PV system benefiting from FiT incentives and under time-varying electricity tariffs.

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1. Introduction

Energy policy incentives across the globe have supported the installation of distributed energy resources at different levels of the energy system [1,2]. From 2010 it was recorded significant increase of PV installation due to the decrease of the module cost and the implementation of incentive-based programmes like the FiT policies [3,4]. The recent changes in the FiT policies for example in the UK and the closure of the Renewable Obligation scheme applied to a small-scale solar PV with a capacity less than or equal to 5 MW will drastically affect the scale of domestic PV installations [5,6]. In some countries, for example, Germany, a FiT scheme that favours installation of battery storage to maximise self-consumption is already in place [7]. The intermittent nature of solar PV and the mismatch between customer-sited solar PV power

☆ Information about the data underpinning the research work reported here which can be made available can be found in the Cardiff University data catalogue at http://doi.org/10.17035/d.2017.0038094155.

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http://dx.doi.org/10.1016/j.apenergy.2017.06.043
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Nomenclature

Sets
d day = 1–365.
t hour = 1–48 (30 min timestep)

Parameters
$P\_pv(d,t)$ generated PV Power at every time step (kW)
$P\_dmd(d,t)$ electricity demand at each time step
p_FIT generation FiT (pence/kWh)
p_export export FiT (pence/kWh)
p_retail standard retail electricity tariff (pence/kWh)
Δt optimisation time step: half-hourly
$P\_dmd\_unmet(d,t)$ unmet electricity demand at each time step (kW)
$P\_pv\_excess(d,t)$ excess electricity from PV at each time step (kW)
$P\_pv\_onsite(d,t)$ PV power output used for self-consumption (kW)
$Pch\_\min$ minimum battery charging power (kW)
$Pch\_\max$ maximum battery charging power (kW)
$Pdis\_\min$ minimum battery discharging power (kW)
$Pdis\_\max$ maximum battery discharging power (kW)
e^c battery charging efficiency
e^d battery discharging efficiency
$Ebatt\_\min$ battery minimum energy state of charge (kWh)
$Ebatt\_\max$ battery maximum energy state of charge (kWh)
M an arbitrary number that should be big enough to ensure a feasible solution

$TotalPV\_generated$ the total kWh generated by the PV system that is eligible for the export tariff
$TotalPV\_exported$ the amount of kWh exported to grid that is eligible for the export tariff

Variables
$P\_pv\_\mathrm{export}(d,t)$ PV power sold to the grid at each time step (kW)
$P\_grid(d,t)$ Grid Electricity Imported at each time step (kW)
$P\_charge(d,t)$ the power used to charge the battery from excess PV (kW)
$P\_charge\_grid(d,t)$ the power used to charge the battery from the grid (kW)
$X(d,t)$ a binary variable that prevents buying and selling of electricity simultaneously at each time step
$Y(d,t)$ binary variable at each time steps that constraints charging power to prevent charging and discharging simultaneously
$Z(d,t)$ binary variable at each time steps that constraints discharging power to prevent charging and discharging simultaneously
$P\_discharge(d,t)$ the power discharged by the battery to meet unmet demand (kW)
$E\_s(d,t)$ battery energy state of charge at each time step (kWh)
$E\_s(d,t-1)$ battery energy state of charge at the previous time step (kWh)

output and the residential electricity load profiles makes battery storage a potential option to maximise savings [8–10].

The cost of battery packs is falling, about 25% reduction for lithium-ion battery between 2009 and 2014 according to [1]. The domestic electricity storage battery could provide support to an existing customer-sited PV enrolled in FiT incentivised schemes. According to [11], the value of the California's Public Utilities Commission policy on supporting affordable solar PV installations in multi-family housing could be enhanced by battery storage systems. This means that the value proposition for solar PV owners in respect to changes in the electricity rates and tariffs could be improved considerably with a well-managed battery energy storage system. In Spain for example, the parliament have signed an agreement to remove the decree against self-consumption [12,13]. This shows a clear opportunity for the deployment of battery energy storage in existing and new PV systems benefiting from FiT schemes. Maximising the use of battery storage for grid connected residential solar PV applications has been studied and the benefit to distribution network operators has been demonstrated in [7,14–16]. By optimising the operation of battery storage coupled to a residential PV the effect of variable PV output is minimised. Smart tariffs have the potential to encourage the adoption of distributed energy systems, as it has been widely used in California and Australia for managing high demand charges [17,18]. In the UK the economy 7 and 10 tariffs are used as a two-tier tariff for customers with storage heaters [19–21]. A triad peak energy demand predicting model for buildings was developed in [22], which is relevant because electricity customers are becoming sensitive to electricity tariffs at hours with low price/kWh periods. Linear programming and MILP methods using optimisation software tools have been proposed for maximising the scheduling of distributed energy resources with battery storage systems in [23–25]. In [26–29], an optimal power flow management scheme was proposed for a standalone backup generator. The objective of the work in [28] is to minimise the fuel costs of a backup generator for a residential building using battery energy storage coupled to a grid connected solar PV. In [14,15], a low voltage distribution network operator owned battery storage was used to control the power flows in the network. In [13], smart time of use tariffs was used to maximise daily revenue streams for a residential solar PV connected to a battery storage, however, no FiT incentive was considered in the optimisation process. The work in [7], investigated the use of battery storage in residential low voltage network to defer costly network upgrades, and a multi-objective optimisation formulation to evaluate the trade-offs between voltage regulation, peak power reduction and the annual cost of electricity supply was developed. In [30], an optimisation based approach that maximises daily operational savings for grid connected solar PV customers was presented. An optimal power flow management framework for a grid connected PV with battery storage in order to maximise the peak shaving service is presented in [31]. Another study [32] simulated the impact of using a combination of solar PV, battery storage, Stirling Engine Combined Heat and Power on electricity self-sufficiency, intermittent grid demand and customer economic costs. Other studies [30,33,34] have considered the optimisation of battery storage operation under specific tariff structures. Others have looked into large scale operational planning of renewable energy sources (PV and wind power) in combination with battery energy storage [35–38]. The references (for example, [26–29,31,39]) focused on using time-varying tariff structures to optimise the operation of customer-owned solar PV in combination with battery storage system over a 24 hour period. In [39], the optimal benefit of battery energy storage was only computed for a typical day in summer and winter and then computed for the year using projected estimates. Maximisation of FiT revenue streams at the customer premises for existing and new PV generating systems benefiting from FiT incentive (generation and export tariff) and under time-varying electricity tariff schemes can be achieved by using battery storage. To the extent of the author's knowledge, no literature reviewed has developed an optimisation problem that evaluates the value of deploying battery storage for an existing PV system with real PV data (benefiting from FiT incentive) under different electricity tariffs and for a new PV system in which the impact of unit cost (£/kWh) on the adoption of battery storage is investigated. Therefore, in this paper, an MILP optimisation formulation was developed and real PV generation data was used to simulate power flows for a complete year. The main aim of this research was to evaluate the value of deploying a stationary battery storage for existing and new PV system benefiting from FiT incentive and under time-varying electricity tariffs. For running the optimisation model for the existing PV system, a set of real half-hourly PV output data and residential load data over a period of one year were used compared with work in [27,28,39,40], where the data of a certain period of the year was used. In a second step when the PV system is modelled as a new system, the electricity demand data, solar irradiance, tariff and battery unit cost were used to analyse the effect of battery storage unit cost on the adoption of battery storage in maximising FiT revenue. The new PV system is simulated in DER-CAM software tool by modifying the optimisation formulation in DER-CAM to include PV onsite generation and export tariff incentive. Previous DER-CAM applications considered net metering and the effect of demand charges on the adoption of onsite distributed energy resources, but there is no DER-CAM application modelled with generation and export tariff.

The main technical contributions of this paper are as follows:

- An optimisation model was developed to evaluate the benefit of battery storage on FiT revenue streams for an existing PV system on a yearly and half-hourly basis.
- Real residential PV generation data was analysed and included in the optimisation model to increase its revenue maximisation accuracy and to accommodate complex real weather conditions.
- Sensitivity analysis was carried out to evaluate the impact of battery storage capacity (kWh) on the objective function.
- DER-CAM optimisation was modified to include FiT incentive (generation and export tariff).
- The impact of storage unit cost on the adoption of battery storage for the new PV system was investigated in DER-CAM.

The rest of the paper is structured as follows. In Section 2 a literature review on the state of the art PV – battery storage systems with tariff incentives and time-varying electricity tariffs are presented. In Section 3, a description of the optimisation model with the PV system modelled as an existing system and its full mathematical formulation describing the optimisation formulation and data input is presented. Section 4 gives a brief description of the modification made in DER-CAM to include FiT (generation and export tariff) for a new PV system. The data input into DER-CAM can also be found in Section 4. In Section 5, the three case studies considered for the PV modelled as an existing system are presented. Section 6 describes the case studies considered when the PV system is modelled as a new system in DER-CAM. Discussion regarding of the results in Sections 5 and 6 are provided in Section 7. Concluding remarks can be found in Section 8.

2. Literature review

Grid connected solar PV with battery systems have been extensively studied to simulate and quantify the optimal benefits of deploying such systems at the customer level. Some of the system level studied in the literature include simulation and optimisation of PV – Battery systems based on self-consumption, FiT incentives trends, wholesale electricity tariffs and demand forecasting [41–46]. Batteries have been widely used in standalone PV systems [47]. Batteries in grid connected PV systems are recently gaining attention in grid connected PV systems under FiT and time of use tariffs [48]. Domestic solar PV despite having high installation costs have high adoption rates which are largely driven by energy policies, for example, FiT schemes in Europe and other parts of the world [1,40,49]. Large scale installations in the form of solar farms are also common due to favourable energy policies [50].

According to [23,51,52], battery adoption in energy systems with high shares of fluctuating distributed energy resources can mitigate against high-frequency interruption caused by a specific electricity demand or grid connected distributed energy systems. An important issue in this context is to justify why the need for battery storage in electricity networks. Peak electricity demands in power systems are increasing and high shares of distributed energy resources create a mismatch between generation and demand. This means a poor utilisation of generation, transmission and distribution infrastructure according to [52]. Battery storage with PV systems can be leveraged by utility operators to maximise the usage of existing network capacity and defer network investments. Thus, the capacity for residential electricity customers to provide an effective response to dynamic electricity pricing will become increasingly valuable for integrating the high penetrations of distributed energy resources like PV to the future electricity network. In [44], the effects of active demand side management and battery storage system in the amount of self-consumption was studied. The relationship between electricity energy flows and battery storage capacity was shown to be an important decision variable. The study in [53], investigated the viability of FiT schemes for enhancing the development of renewable energy technologies. A sensitivity analysis of the model in [53] was simulated to reveal the significant parameters affecting the FiT model. Flat rate electricity tariffs with no daily or yearly variation have been in use in both developing and developed countries, however, such tariff has little incentives to encourage electricity customers to modify their demand and adopt distributed energy resources [19,54]. With the increasing deployment of smart metering schemes in residential customer premises and decreasing FiT incentives according to [41], smart tariffs and real time pricing are becoming a popular option in residential PV – battery systems. A combination of distributed energy technologies (PV, wind, energy storage) and existing electricity tariff rates to provide benefit to residential customers are not clear and well understood [55]. Smart electricity tariffs are highlighting critically important hours of a year by introducing an extremely high rate so that the demand is attempted to be limited within the range of network capacity. The flexibility of aggregated demand profiles in buildings and wholesale electricity market predictions are studied in [56]. The optimisation model in [56] is implemented for a scenario of aggregated demand profile which enables an aggregator to participate in the day-ahead market. In other applications, minimising expensive demand charges (kVA charge) has been a key driver for deploying PV – battery systems, see references [18,57,58].Due to the significant difference between the flat retail electricity price and the FiT export tariff for PV, the work in [40] investigated the value of battery storage deployment to maximise FiT revenue stream. A battery storage optimisation was performed to maximise FiT which aims to find the periods of the highest electricity prices as discharging time slots and periods with the lowest electricity prices as charging time slots. In [59], an MILP model for managing and sizing residential heat pumps to maximise self-consumption of PV generation was developed. The PV generation profile was generated based on irradiation data. The work in [60] introduced a case study to use battery storage size economic optimisation to help customers choose the best battery storage technology for their needs. The paper compares battery energy storage system intra-day discharge strategies that could make battery storage financially rewarding to the owner. A simulation-based optimisation model using the regulatory framework in Germany was developed to assess the impact of different electricity demand profiles on cost optimised battery storage design and operation [45]. The model was simulated with a focus on single family homes with PV systems smaller than 10 kW. The authors in [45] recommended the use of realistic electricity load profiles to avoid optimistic optimisation results. In [9], the objective function of the optimisation of battery storage for a distributed PV generation was formulated based on real PV and load data and the authors suggested national incentive policies such that PV systems are rewarded for battery system usage and implementation. This will make viable deployment options for the adoption of PV – battery systems for the management of peak demand and deferment of investments in distribution networks. A FiT scheme which rewards self-consumption was developed in [61]. This was achieved by developing an optimisation problem which calculates the incentive and the optimal sizes of PV and battery storage. In [41], a simulation model was presented to identify the most profitable sizes of PV and battery storage systems based on residential customers perspective. The key drivers for profitability, self-consumption and self-sufficiency were further explored in [41]. The need for enhanced economic model and profitability estimation of battery storage systems with PV was explored in [62]. The authors in [62] identified the importance of optimisation of battery storage sizing, replacement schedule and deployment of different operational strategies in the future. Look-ahead energy management for residential PV with battery storage under time of use electricity rates was designed in [63]. The work in [63] also developed a load forecasting module based on the Kalman filter with an energy management system to minimise the use of electricity using time of use pricing.

Maximising self-consumption is increasingly becoming an important factor in grid connected PV – Battery Systems. In [64], a model was developed to quantify the level of self-consumption that can be expected for a residential PV with or without battery storage system. The model in [64] was simulated with synthetic PV data. The work in [64] also shows that the benefits of self-consumption come from available tariff structure and the difference between electricity buying and selling prices, which depends on local regulation.

3. Optimisation problem for existing PV system

This section describes the optimisation model for maximising FiT revenue for the existing PV system with and without battery storage.

The optimisation model is formulated as an MILP problem and solved in Advanced Interactive Multidimensional Modelling System (AIMMS) [65]. AIMMS is an integrated development environment that allows developers to create customised solutions. It enables the development of optimisation models through a unique set of design tools for model building, data modelling and graphical user interface creation. Results can easily be validated by creating visual representations of the outcomes [66]. The flexibility of AIMMS (i) ensures model separation from data, (ii) makes it easy to repeat different scenarios with new datasets and (iii) easily scale up to larger models. Fig. 1 shows the optimisation model flowchart.

3.1. System model

The system studied is shown in Fig. 2. The PV is an existing system benefiting from the FiT scheme. The main components of the system in Fig. 2 is the existing PV generation system, the proposed battery storage, customer aggregated electricity loads, the low voltage grid and power electronic converters.

The optimisation model seeks to optimise the battery storage charging and discharging to maximise FiT revenue for the existing PV owner. The large difference between the generation tariff and export tariff makes it attractive for battery storage systems. The battery storage system has the potential to maximise self-consumption for solar PV owners benefiting from the FiT scheme. The battery storage system can maximise the usage of peak solar PV output power by storing excess PV power output for use in the expensive peak time of use tariff hours as illustrated Fig. 3. Thus, avoiding high electricity costs in such hours.

3.2. Mathematical formulation

3.2.1. Objective function

The optimisation model is indexed by the sets *(d, t)*, where *d* is the set of days in a year ($1 \leq d \leq 365$) and *h* is the set representing the half-hour periods in each day ($1 \leq h \leq 48$).

The objective function presented in Eq. (1) maximises the FiT revenue streams and minimise the grid electricity import for an existing residential solar PV with and without the installation of battery energy storage. This is evaluated for three import tariff cases (i) flat retail tariff (ii) Economy 7 tariff and (iii) varying wholesale electricity tariff.

$$\begin{aligned} Objective\ Function = max\sum_{(d,t)}(&P\_pv(d,t) \times p\_FIT \\ &+ P\_pv\_\text{export}(d,t) \times p\_\text{export} \\ &- P\_grid(d,t) \times p\_retail) \times \Delta t \end{aligned} \tag{1}$$

The objective function in Eq. (1) is modified to include the economy 7 tariff and wholesale tariff. The new equation with the wholesale electricity tariff is shown in Eq. (2).

$$\begin{aligned} Objective\ Function = max\sum_{(d,t)}(&(P\_pv(d,t) \times p\_FIT) \\ &+ (P\_pv\_\text{export}(d,t) \times p\_\text{export}) \\ &- (P\_grid(d,t) \times p\_wholesale) \\ &- (P\_charge\_grid(d,t) \times p\_wholesale) \\ &+ (P\_discharge(d,t) \times p\_wholesale)) \times \Delta t \end{aligned} \tag{2}$$

The objective function computes the net revenue from onsite generation $P\_pv(d,t)$ and the export of electricity $P\_pv\_\text{export}(d,t)$. The model parameters and decision variables are described in the following sections.

3.2.2. Model constraints

The optimisation model is subject to the following constraints:

$$0 \leqslant P\_grid(d,t) \leqslant P\_dmd\_unmet(d,t) \tag{3}$$

$$\begin{cases} \text{if } P\_dmd(d,t) > P\_pv(d,t), \text{ then} \\ \quad P\_dmd\_unmet(d,t) = P\_dmd(d,t) - P\_pv(d,t) \\ else \\ P\_dmd\_unmet(d,t) = 0 \\ endif \end{cases} \tag{4}$$

$$0 \leqslant P\_pv\_\text{export}(d,t) \leqslant P\_pv\_excess(d,t) \tag{5}$$

$$\begin{cases} \text{if } P\_pv(d,t) - P\_dmd(d,t), \text{ then} \\ \quad P\_pv\_excess(d,t) = P\_pv(d,t) - P\_dmd(d,t) \\ else \\ P\_pv\_excess(d,t) = 0 \\ endif \end{cases} \tag{6}$$

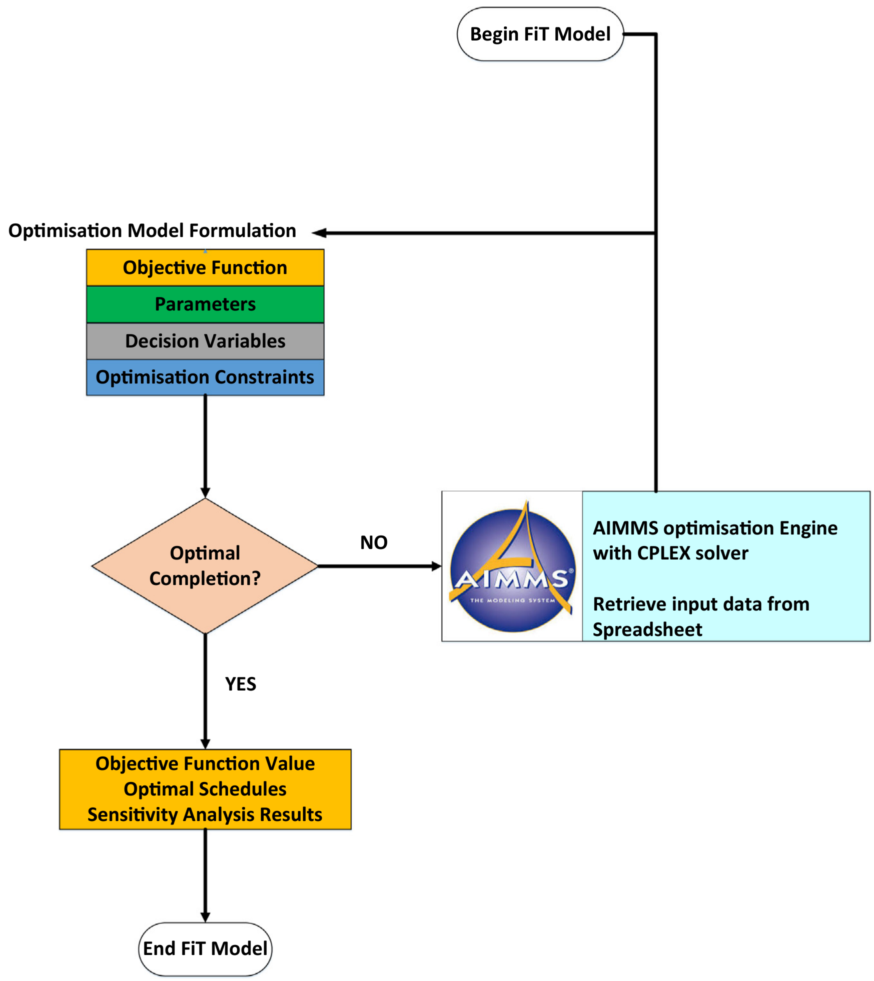

Fig. 1. Optimisation model flowchart.

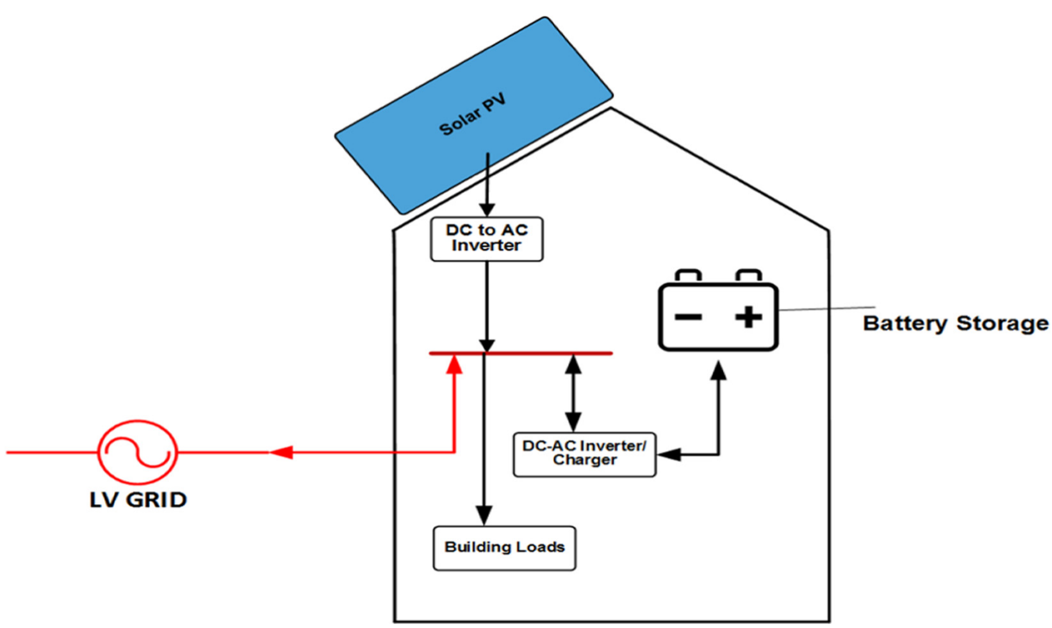

Fig. 2. Residential PV-Battery storage configuration [67]

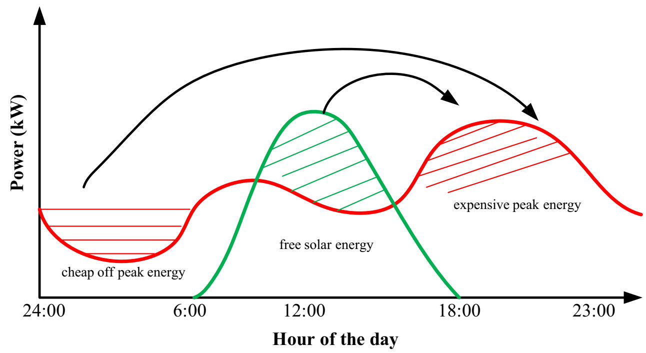

Fig. 3. Potential of shifting energy usage and power flows with battery storage.

From the previous equations describing the constraints, it is seen that constraint (3) limits the grid electricity imported to the unmet electricity demand and (4), constraint (5) limits the amount of PV for export to the excess PV which is calculated in (6).

The objective function is modified to include battery charging and discharging schedule when battery storage is considered in the model (See Eqs. (1) and (2)). With battery storage coupled to the existing PV generation system the following constraints are added to the model:

$$Y(d,t)Pch\_\min \leqslant P\_charge(d,t) \leqslant Y(d,t)Pch\_\max \tag{7}$$

$$Z(d,t)Pdis\_\min \leqslant P\_discharge(d,t) \leqslant Z(d,t)Pdis\_\max \tag{8}$$

$$Y(d,t) + Z(d,t) \leqslant 1 \tag{9}$$

$$\sum_{(d,t)} P\_discharge(d,t) \leqslant \sum_{(d,t)} P\_charge(d,t) \tag{10}$$

$$E\_s(d,t) = E\_s(d,t-1) + \left(e^c P\_charge(d,t) + e^c P\_charge\_grid(d,t) - \frac{P\_discharge(d,t)}{e^d}\right) \tag{11}$$

$$P\_pv\_export(d,t) \leqslant M(1 - X(d,t)) \tag{12}$$

$$Ebatt\_\min \leqslant E\_s(d,t) \leqslant Ebatt\_\max \tag{13}$$

$$P\_grid(d,t) \leqslant MX(d,t) \tag{14}$$

$$P\_grid(d,t) + P\_pv(d,t) - P\_pv\_export(d,t) - P\_charge(d,t) - P\_charge\_grid(d,t) + P\_discharge(d,t) = P\_dmd(d,t) \tag{15}$$

$$P\_pv\_export(d,t) \leqslant P\_pv(d,t) \tag{16}$$

$$P\_grid(d,t) \leqslant P\_dmd\_unmet(d,t) \tag{17}$$

$$P\_discharge(d,t) + P\_grid(d,t) = P\_dmd\_unmet(d,t) \tag{18}$$

Constraints (7)–(18) incorporates the battery storage limitations for charging and discharging.

Once the optimisation model is executed, a set of solutions is produced for each day of the year and each half-hour period of each day of that year.

3.3. Assumptions

The validity of the developed optimisation model for charging and discharging of the battery storage system coupled to an existing PV generation system benefiting from the FiT scheme is based on the following assumptions:

- The residential customer has an existing PV generation system enrolled in a FiT scheme. This scheme sets the generation tariff at 12.57 p/kWh and the export FiT at 4.64 p/kWh [40].
- A smart meter is installed at the customer premises, as such export is accurately measured.
- The battery storage specifications were taken from [67,68].
- The optimisation model for managing the battery storage charging and discharging coupled to the existing PV generation system is simulated using historical electricity demand and real PV power output data of a residential customer obtained from [69,70].

3.4. Data input

3.4.1. Electricity load profile

Half-hourly residential electricity load profiles were taken from ELEXON [70] for a complete year with a minimum load equal to 0.213 kW and the maximum load equal to 0.95 kW.

3.4.2. Residential PV generation data

The PV monitoring data was taken from the Sheffield solar microgeneration database [69,71,72]. The Sheffield microgeneration database records PV generation in the UK by collecting data from voluntary PV owners. Half-hour generation from 50 PV systems was randomly selected from the microgeneration database. The generation data is obtained in the form of cumulative half-hourly meter readings. The total installed capacity of the solar PV generation system used in the optimisation model is 3.36 kW covering an area of 23 m^2 [69].

3.4.3. Residential electricity tariff

The residential retail electricity prices in the UK have fairly seen no variation in recent years and has averaged at 15 p/kWh according to Committee for Climate Change projection [73]. The value of 15 p/kWh is used flat rate electricity import tariff.

3.4.4. Economy 7 tariff

The economy 7 tariff is a time of use tariff offering off-peak hours of low electricity rates beginning as shown in Fig. 4. About 9% of the UK residential electricity customers are subscribed to this tariff [74]. The remaining hours of the day are charged are at a high tariff rate.

3.4.5. Wholesale electricity tariff

The wholesale tariff is a tariff at which electricity is being purchased by energy suppliers, aggregators, energy brokers etc. It varies based on the cost of the marginal source of electricity generation, for example, gas-fired generation (gas price). The wholesale tariff data obtained from [75] is used to evaluate the impact of time-varying tariff rates on the objective function value for existing PV system. Fig. 5 shows a plot of the wholesale tariff data for the year 2015.

Table 1 shows the summary of the wholesale electricity tariff data. It could be seen from Table 1 that the minimum value of the wholesale tariff is negative at about minus 34.98 £/MWh. The minus 34.98 £/MWh is the minimum wholesale electricity tariff in the data referenced in Table 1. The negative 34.98 £/MWh indicates a price signal on the electricity wholesale market that occurs when a high non-dispatchable power generation meets low

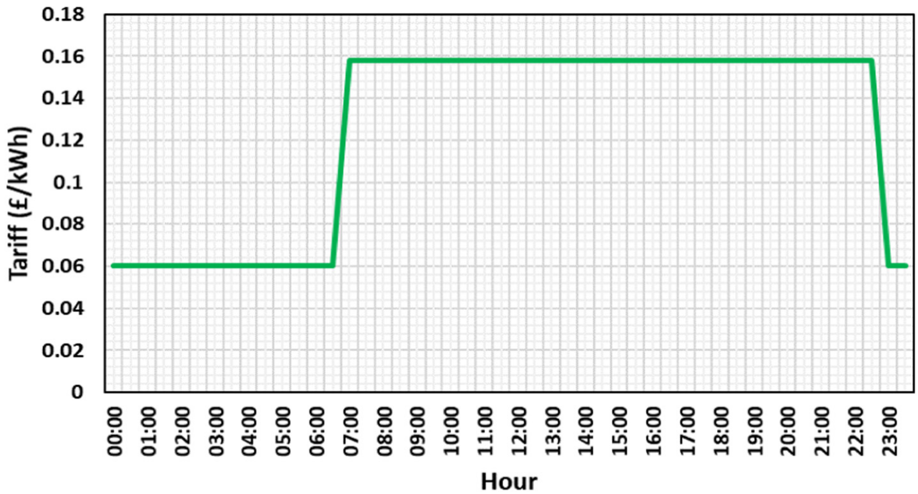

Fig. 4. Economy 7 tariff [19,20].

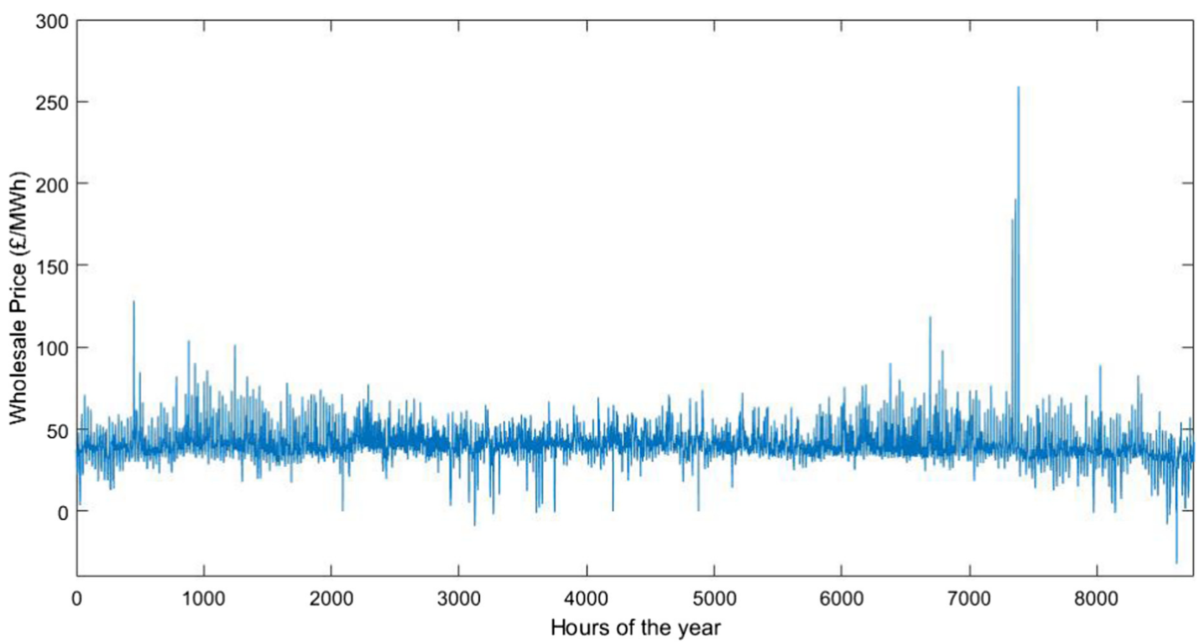

Fig. 5. Plotted wholesale price 2015.

Table 1
Annual wholesale electricity tariff data [75].

Wholesale electricity tariff statistics	
Min (£/MWh)	−34.98
Max (£/MWh)	359.63
Average(£/MWh)	39.9
Standard deviation (£/MWh)	12.82

demand. Non-dispatchable power sources cannot be shut down and restarted in a quick and cost-efficient way. Renewable energy sources like solar and wind are examples of this. The maximum goes up to about 359.63 £/MWh (36 p/kWh) and the standard deviation is about 12.82 £/MWh (1 p/kWh).

3.4.6. FiT data

Different countries have policy incentives that encourage the adoption of distributed energy resources. According to [76] FiT and net metering schemes have seen varying success nationally and globally in countries like USA, Germany and the UK.

The FiT scheme used as a case study in this paper was introduced by the Department of Energy and Climate Change (DECC) on 1 April 2010 as a financial incentive to encourage uptake of distributed energy resources technologies (DERs) [77,78]. Most residential electricity customers with onsite DERs qualify for the scheme. The FiT scheme includes a generation tariff and export tariff. The generation tariff is paid for every kWh of PV generated and the export tariff is paid for every kWh exported.

4. Optimisation problem with the PV modelled as new system

The revenue streams for PV generation systems eligible for tariff incentives will largely depend on the battery installation costs. According to [1], lower battery prices will ensure battery energy storage coupled with existing PV generation systems are attractive with good payback periods. A PV generation system with an option for battery installation is simulated in DER-CAM. DER-CAM was used to determine the battery unit costs (£/kWh) required to make an economically viable investment into battery storage for a new PV generation system using the solar irradiance data of the system described in section 3.

4.1. DER-CAM model

Fig. 6 shows the schematic of the DER-CAM model, the PV capacity (kW) is modelled as a decision variable based on the irradiance data of the location of the PV.

The main aim of the model in DER-CAM is to evaluate the minimum battery unit cost that will make battery adoption viable economically for the PV system under FiT and time-varying electricity tariff (economy 7 tariff).

4.2. Modification in DER-CAM

The detailed mathematical formulation in DER-CAM is reported in [79,80].

The high-level formulation of the objection function is shown in Eq. (19):

$$\begin{aligned}&\textit{Minimise}\\&\textit{AnnualEnergySupplyCost}:\\&\textit{energy\_purchase\_cost} + \textit{amortized\_DER\_technology\_capital\_cost}\\&\quad + \textit{annual\_O\&M\_cost}\end{aligned} \tag{19}$$

Eq. (19) was modified to include FiT tariff incentive (PV generation and export tariff) to model the new PV system with location data of the model described in Section 3. The modification is presented in Eq. (20):

$$\begin{aligned}&\textit{Minimise}\\&\textit{AnnualEnergySupplyCost}:\\&\textit{energy\_purchase\_cost} + \textit{amortized\_DER\_technology\_capital\_cost}\\&\quad + \textit{annual\_O\&M\_cost} - \textit{p\_FIT} \times \textit{TotalPV\_generated}\\&\quad - \textit{p\_export} \times \textit{TotalPV\_exported}\end{aligned} \tag{20}$$

where *TotalPV_generated* is the total kWh generated by the PV system that is eligible for the generation tariff (*p_FIT*), and *TotalPV_exported* is the amount of kWh exported to the grid that is eligible for the export tariff (*p_export*).

4.3. Assumptions

The validity of the modified DER-CAM optimisation model with FiT incentives is based on the following assumptions:

- The PV capacity (kW) is modelled as a decision variable (new PV system) with irradiance data obtained from the longitude and latitude information of the proposed PV system.
- The battery unit cost in (£/kWh) of \$990/kWh (equivalent to £683/kWh) for the battery storage is taken from [81].
- The installation cost of the PV system (3.752 \$/Wp) is taken from the DER-CAM database.

4.4. Data input

4.4.1. Load profile

Half-hourly residential electricity load profiles were taken from ELEXON [70] for a complete year with a minimum load equal to 0.213 kW and the maximum load equal to 0.95 kW. The load profiles were converted to DER-CAM format: day type (weekdays, peak days and weekend days) and for each month of the year.

4.4.2. Solar irradiance

The location (longitude and latitude) of the PV system described in section 3 was used to obtain the irradiance data from [82] and used as input to DER-CAM.

4.4.3. Economy 7 tariff

To simplify the modelling time of use tariff in DER-CAM, the economy 7 tariff data was used. The economy 7 has a two-tier tariff, one for 7 h' off-peak period and the other hours for the peak period (see Fig. 4). It could be seen from Fig. 4 that the off-peak tariff is about 6 p/kWh between the hours (1:00–6:00) and (23:00–24:00). The peak is charged at about 15.8 p/kWh between the hours (7:00–22:00).

5. Case studies for the existing PV system

Three case studies were simulated to evaluate the objective function of the optimisation model in Eqs. (1) and (2).

Case Study 1: In this case study, the existing PV under FiT with no battery storage is buying electricity from the grid with flat electricity tariff. The grid power purchased is evaluated based on the electricity demand profile and the solar PV output profile. Fig. 7 shows the system configuration for case study 1.

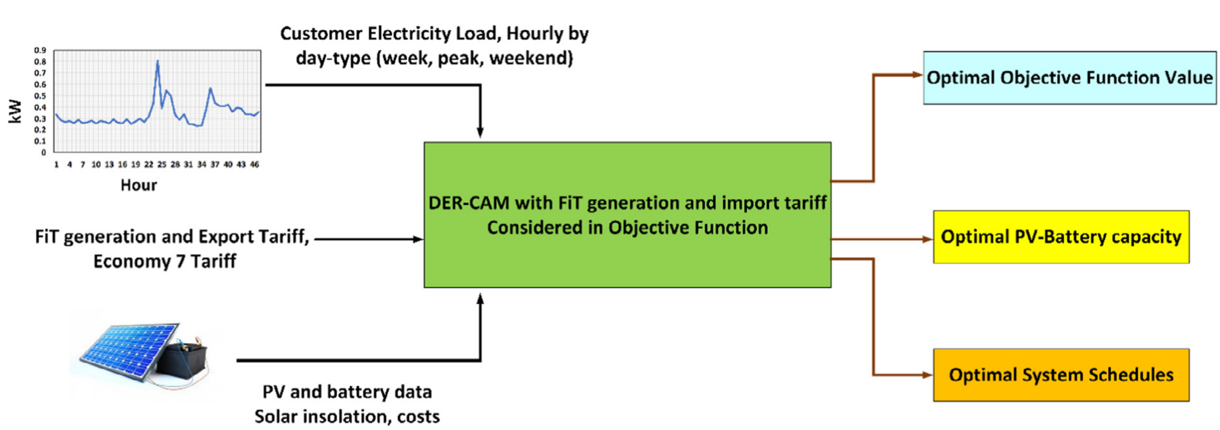

Fig. 6. Schematic of DER-CAM.

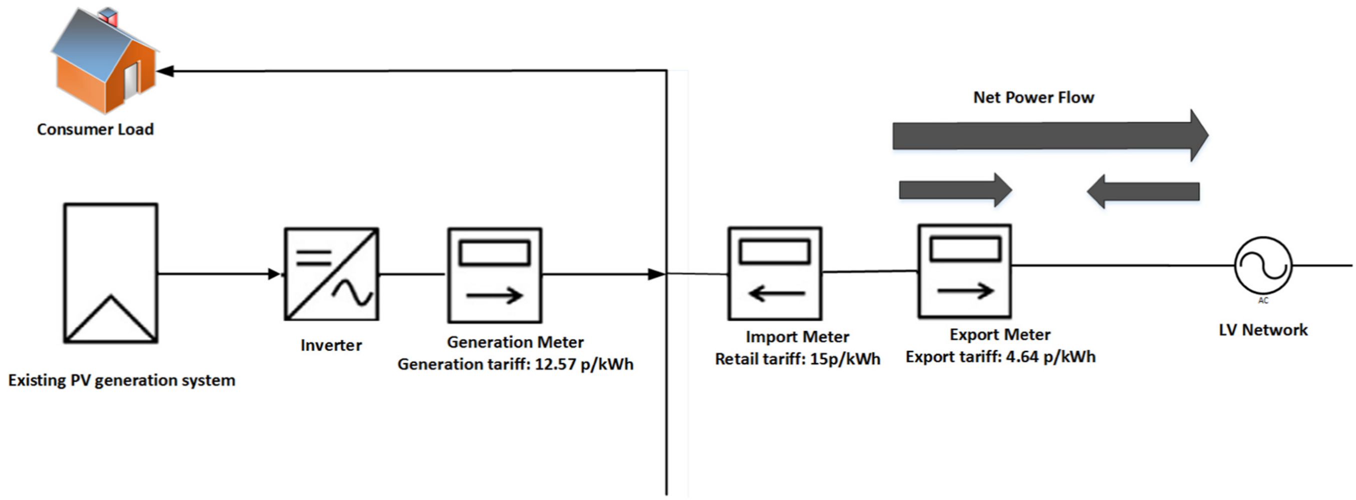

Fig. 7. PV generation system without battery storage.

Case Study 2: This case study considers the existing PV + Battery with FiT and economy 7 tariffs. Fig. 8 shows the system configuration for case study 2.

Case Study 3: This case study has PV + battery storage under the FiT tariff and considering wholesale tariff as electricity import tariff.

Fig. 8 shows the system configuration for case study 3 also. Instead of economy 7 as electricity import tariff, the wholesale electricity tariff is taken from [75] and used in the optimisation model.

A simulation of the optimisation model was performed. For case study 1, an example of optimised power profiles for the system is presented for **winter** (representing high electricity loads and low PV generation) and **summer** (representing high PV power generation and low electricity loads). In case study 2, optimal power profiles for the system in summer and winter are presented. In case study 3, an example of optimal dispatch profiles for the PV – Battery system for the periods of negative, low and high wholesale electricity tariffs are shown.

5.1. Case study 1 results

The results of this case study are evaluated for a typical winter and summer day of the year.

On a winter typical day, early in the morning hours, the grid import is required to meet the electricity demand. This is due to the low solar irradiance. The grid electricity import steadily decreases as the PV generation builds up during the day

Electricity imported from the grid is evaluated and simulated if onsite electricity demand is greater than the PV power output. The amount of PV generation utilised for export and self-consumption is shown in Fig. 9.

The exported power in the winter case is low and much of the PV generation is consumed onsite. When the PV decreases to zero at 15:30 h, the site is starting to import electricity to meet demand. This implies an increase in the total costs to meet the peak electricity demand by importing electricity from the grid. The grid electricity imported (blue curve in Fig. 9) is following the electricity demand (red curve in Fig. 9).

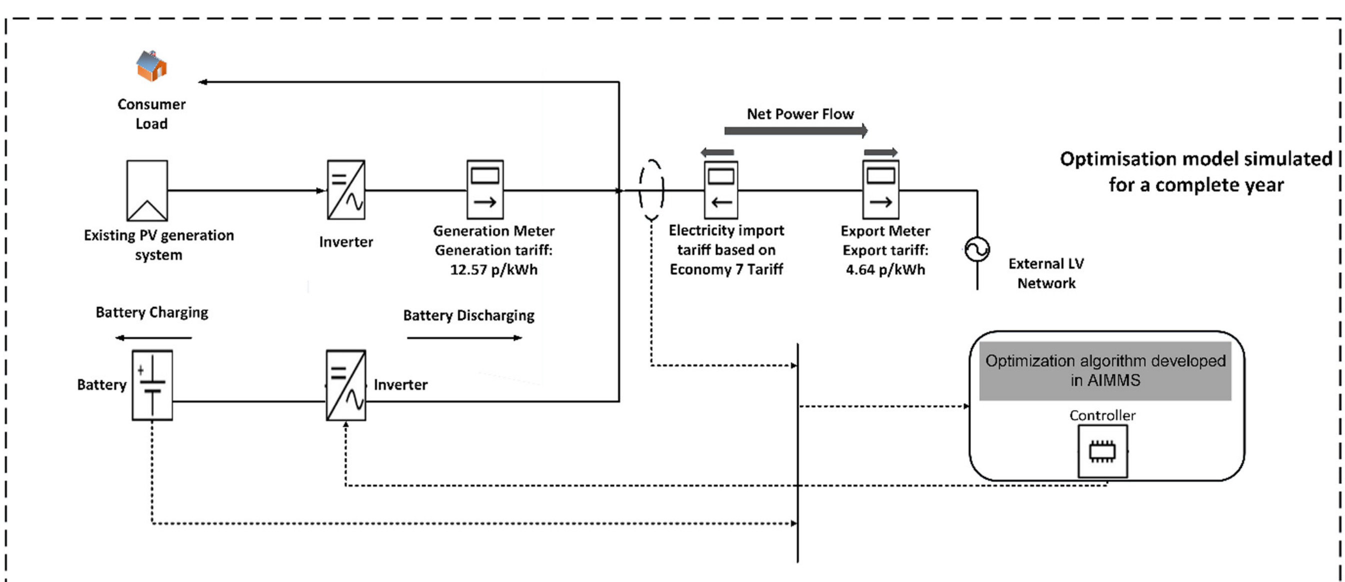

Fig. 8. PV generation system with battery storage (case study 2).

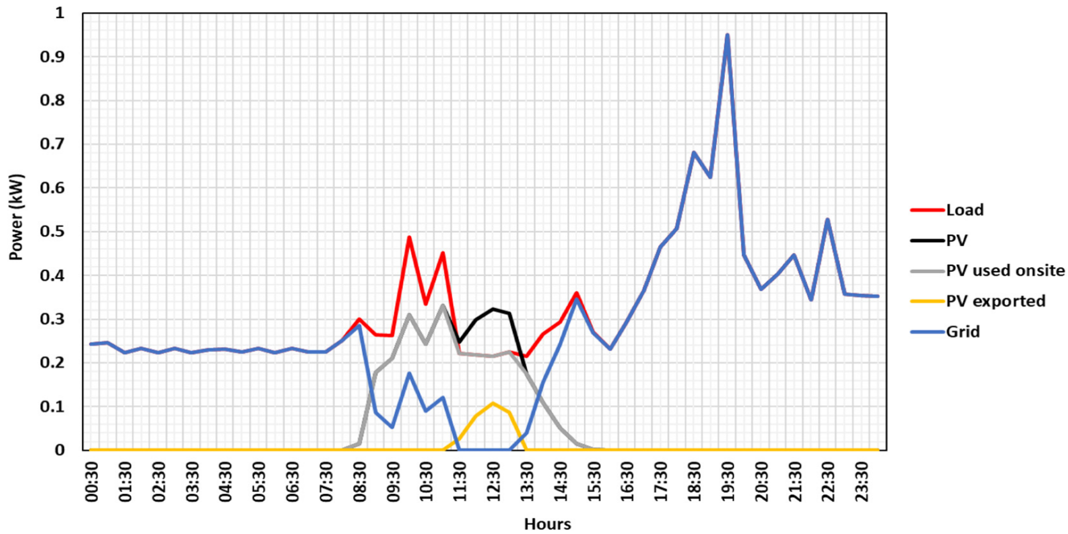

Fig. 9. Power profiles of the PV system with no battery storage (winter).

On a summer typical day, there is a significant generation from the PV by mid-day. The electricity demand is at its minimum compared with the rest of the year. Therefore, the electricity imported from the grid is low and the export of PV power increases as shown in Fig. 10. However, because there is no battery storage installed at the site, the excess PV electricity generated is sold at the low export tariff (4.64 p/kWh).

5.2. Case study 2 results

This case study shows the impact of time varying tariff economy 7 tariff on the existing PV – Battery system. Fig. 11 shows the power profiles of the system on a typical winter day. The grid electricity purchased is highest when the economy 7 tariff is lowest and the battery storage charges from the grid and PV between hours 7:00–10:30 and discharges at the expensive grid hours 19:00–22:00.

On a typical summer day represented by Fig. 12, PV power generation is significantly higher than electricity demand, therefore battery charging (from grid and PV) is limited by the battery capacity and the excess PV generation is exported to the grid at the low FiT export tariff of 4.64 p/kWh. It could be seen that compared to the winter period in Fig. 11, the value of battery storage is lower in the summer periods when PV generation is greater than electricity demand.

However, this could be the reverse especially in locations like California where the summer represents periods of peak electricity demand due to additional demand for cooling loads.

5.3. Case study 3 results

Over the course of a year, electricity demand and PV power generation are changing as seen from the historical PV generation data (due to varying weather conditions and energy consumption behaviour). This case study presents the optimal flow of power for an existing PV generation system combined with a battery storage to maximise the FiT revenue streams.

Fig. 13 shows the year-round plots of parameters and decisions variables of the optimisation model. The purple line on the secondary axis represents the wholesale electricity tariff used as electricity import tariff. The upper plot in Fig. 13 shows the decision variables of the optimisation model with the wholesale electricity plotted on the secondary axis. It could be seen that the battery charges with maximum power with grid electricity in periods with

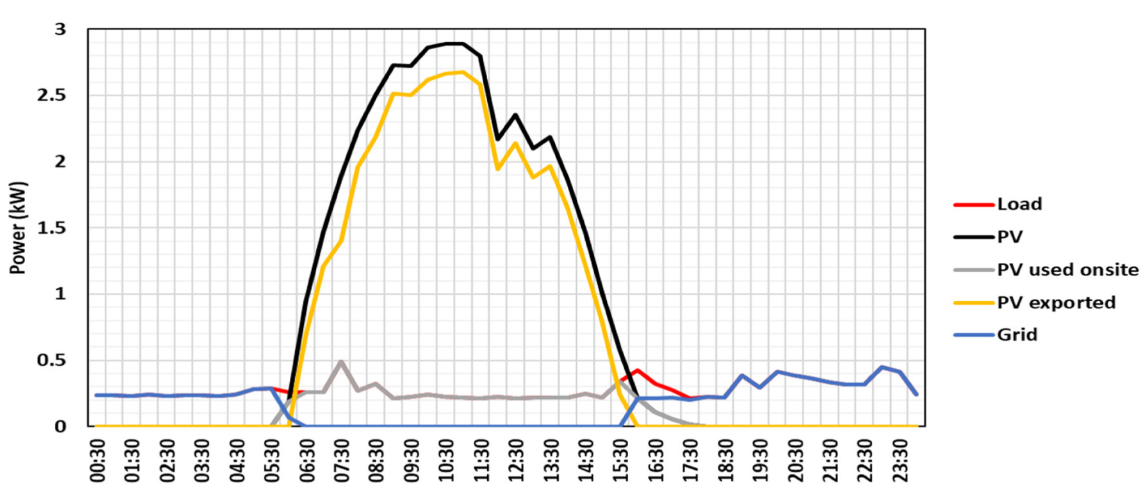

Fig. 10. Power profiles of the PV system with no battery storage (summer).

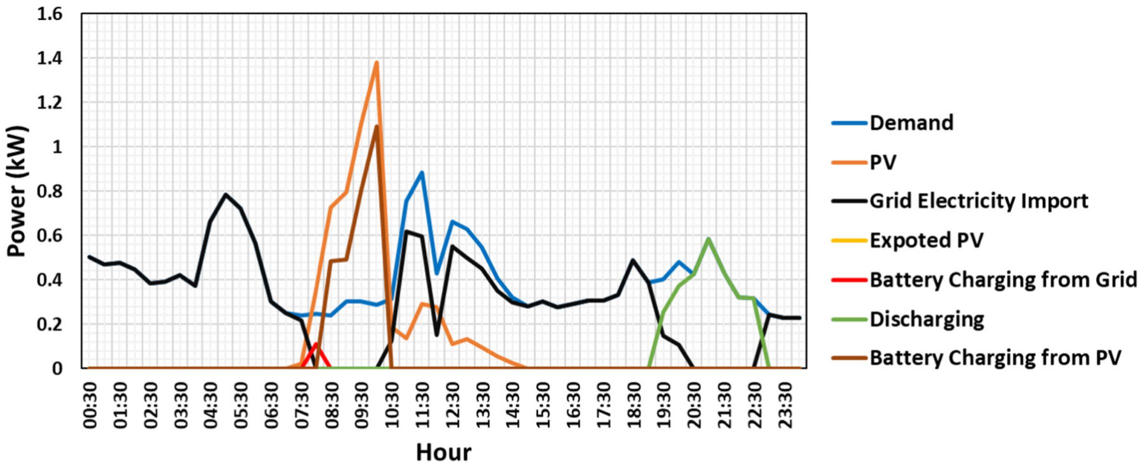

Fig. 11. Optimal power profiles of the system with economy 7 tariff (winter).

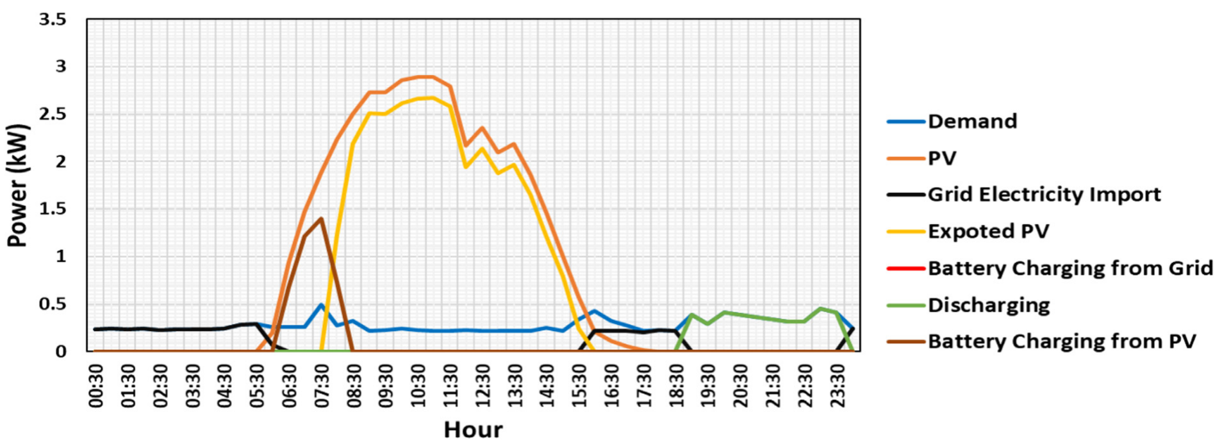

Fig. 12. Optimal power profiles of the system with economy 7 tariff (summer).

negative wholesale electricity tariff. Furthermore, the electricity purchased from the grid is minimised within the negative wholesale tariff periods as shown in the lower plot of Fig. 13.

To better understand the condensed plots in Fig. 13, three examples, representing periods of negative, low and high wholesale electricity tariff over the course of the year are presented. This is done to elaborate the results of the optimisation model in three distinct periods of the wholesale tariff (negative, low and high wholesale tariff periods).

5.3.1. Negative wholesale tariff periods

Negative prices are a price signal on the electricity wholesale market that occurs when a high non-dispatchable power generation meets low demand. Non-dispatchable power sources cannot be shut down and restarted in a quick and cost-efficient way. Renewable energy sources like solar and wind are examples of non-dispatchable power sources. In the context of this paper negative wholesale tariff was chosen from the wholesale electricity tariff data (obtained from [75]) in a typical day of the year with negative prices.

On a typical day within the year when hours (04:30–06:30) have negative wholesale electricity tariff price (dashed line on the secondary axis of Fig. 14), the battery charges from the grid (red line). This is because the negative wholesale price implies that customers are paid to consume electricity, therefore cheap electricity is available for charging the battery storage. With this low wholesale electricity tariff, the optimisation model developed options to export the excess of electricity from the PV system at 4.64 p/kWh while using the residual generation for self-consumption.

Starting at 16:00 h, the solar PV generation drops to zero, and grid electricity import steadily rises (black line), and drops to zero when the wholesale electricity price suddenly increases. The battery that was charged with negative wholesale electricity tariff is discharged between the hours (19:30–22:30) to minimise grid purchase associated with the sudden rise of wholesale electricity tariff. This shows that self-consumption is maximised and grid electricity import is minimised within that period.

5.3.2. Low wholesale tariff periods

The low wholesale tariff period (within the dataset obtained from [75]) is defined as the day with the minimum set of wholesale electricity tariff.

Fig. 15 presents the same optimisation process of battery charging and discharging but in this case, low wholesale electricity tariff period is considered. It could be seen that the grid electricity import (black line) follows and match the electricity demand (blue curve) in the hours where PV generation is zero.

However, when PV generation begins (brown line) to ramp up at hour 08:30, PV generation is used to meet the onsite demand and the generation excess is used for export at 4.64 p/kWh. The grid electricity import becomes zero within this period. At hour 11:30 when the wholesale price drops below 5 p/kWh, the PV export (yellow line) begins to reduce and charging from the grid

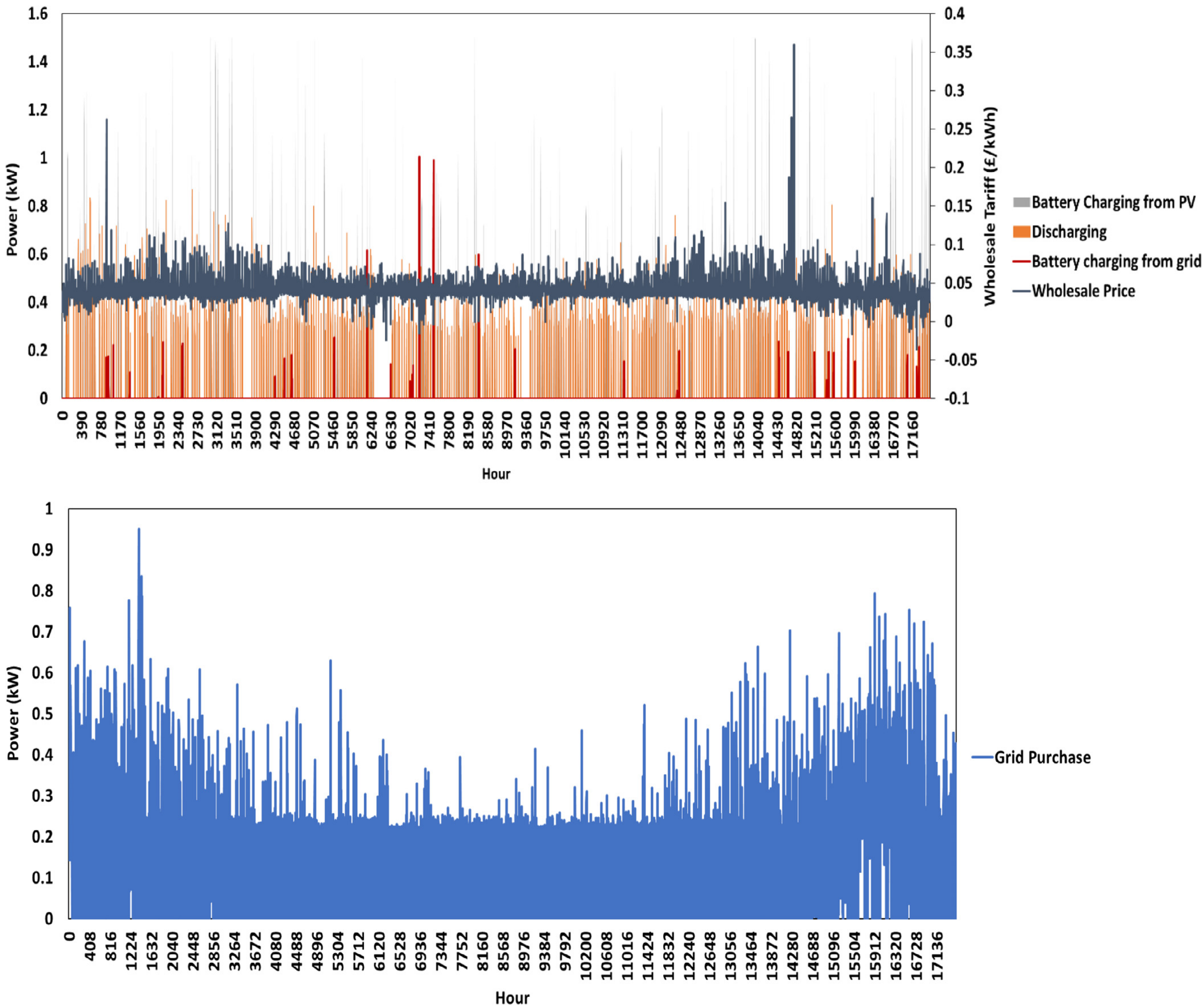

Fig. 13. Optimisation decision variables results over a period of one year.

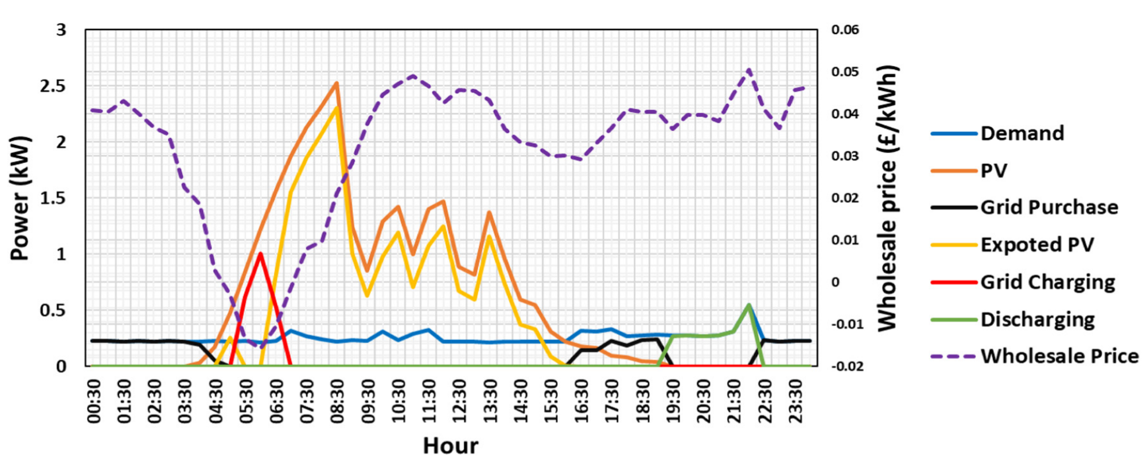

Fig. 14. Optimal power profiles for the system with negative wholesale tariff.

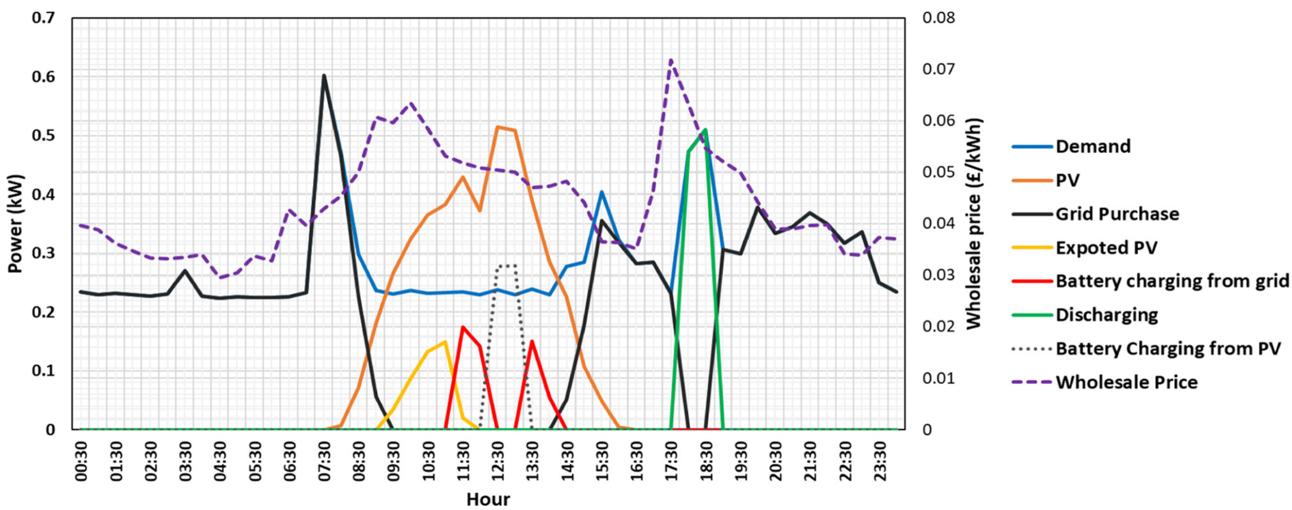

Fig. 15. Optimal power profiles of the system with low wholesale tariff.

begins, and this drops to zero at 12:30 when solar PV generation is highest. At that point, the battery charges from the excess PV generated (ash dotted line).

As the wholesale electricity tariff continue to drop and the PV generation reduces, the battery charges from the grid again (red line). When the electricity demand of the building ramps up at 15:30, and the wholesale tariff is less than 4 p/kWh, grid electricity is used to meet this demand. The battery discharges (green line) between the hours 17:30 and 19:30 when the wholesale electricity tariff is highest, this in turns avoid relatively high grid purchase costs within that period.

5.3.3. High wholesale tariff periods

The high wholesale tariff periods (within the dataset obtained from [75]) is defined as the day with the maximum set of wholesale electricity tariff values.

In this section, an optimal schedule example for the existing PV generation system within a period of extremely high wholesale electricity tariff is presented. Fig. 16 shows that the grid electricity import matches the building electricity demand from 00:30–08:30 when the PV system is not generating electricity.

However, when the PV generation system begins to produce electricity, and the wholesale electricity tariff is just below 5 p/kWh, the battery charges from the excess PV generation (ash dotted lines) equivalent with the battery's charging capacity. This occurs after onsite PV generation requirement has been met. The remaining surplus, after the battery is charged, is exported (yellow line). As the wholesale electricity tariff drops further, between hours 13:30 and 15:30 and the PV generation drops, the battery is charging from the grid (red line).

It was observed that at hour 16:30, the wholesale electricity tariff begins to ramp up, and reaches a maximum of 26 p/kWh at hour 18:00. This maximum value is 11p greater than the retail price of electricity (15 p/kWh). Within this period, the battery discharges (green line) and avoids the high electricity cost associated with importing electricity from the grid.

5.4. Sensitivity analysis and objective function summary

In this section, the results of sensitivity analysis carried out for case study 3 to evaluate the impact of battery capacity (kWh) on the objective function value are presented.

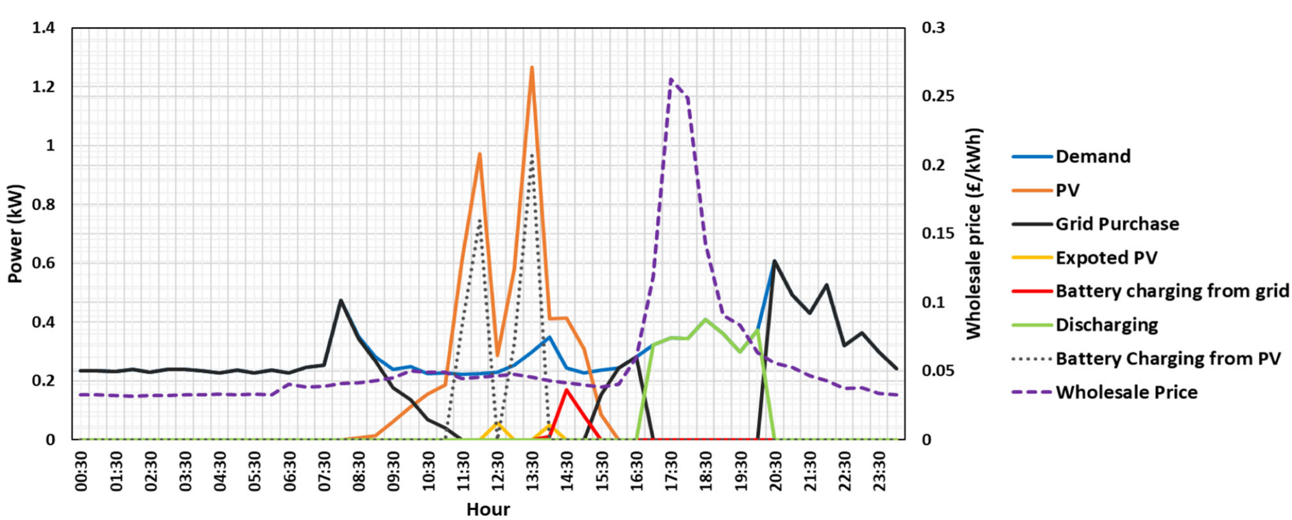

Fig. 16. Optimal power profiles for the existing PV system with battery storage and high wholesale tariff.

In addition, the summary results of the study case 1, 2 and 3 are presented in terms of the objective function in Eqs. (1) and (2).

5.4.1. Sensitivity analysis

To evaluate the effect of the battery size in (kWh) on the objective function of case study 3, a sensitivity analysis was carried out using the procedure in the developed optimisation model. The procedure is expressed as follows:

for (i) *do*
  $Ebatt := BatteryCapacityPoints(i)$
  $Run\ MainOptimizationExecution;$
  $OptimalBenefit(i) := TotalBenefit;$
endfor

The sensitivity analysis is carried out by varying the battery capacity (kWh) parameter in the optimisation model and performing a simulation to quantify the impact of that parameter on the objective function. This is utilised as a strategy to find the optimal battery capacity that maximises the objective function.

The optimal solution procedure is looped over varying battery capacity sizes and the optimisation procedure is run over this loop. Fig. 17 shows the effect of this procedure for case study 2. In Fig. 17, the *x*-axis is representing the range of energy capacities in kWh considered and the *y*-axis is representing the objective function value. The revenue increases as the battery size increase until 3 kWh of battery size capacity is reached and no further increase in revenue is obtained. This shows that the optimal battery storage size for the load and PV dataset used in this work could be increased to 3 kWh for a marginal increase in revenue.

Such a procedure can be used to evaluate the battery storage capacity that will maximise revenue streams for an existing residential PV generation systems under time-varying electricity tariffs and FiT.

5.4.2. Objective function for case study 1 and 2

Table 2 shows the objective function value obtained after a year's operation of the existing PV generation system for case studies 1, 2 and 3.

It was found that for the wholesale electricity tariff, the objective function increases from £314 in the base case (case study 1) to £482.28 with economy 7 tariff (case study 2) and £507.28 with wholesale electricity tariff (case study 3). With time, varying smart electricity tariffs and falling battery costs, the economic case for battery storage coupled to an existing PV generation system could be enhanced.

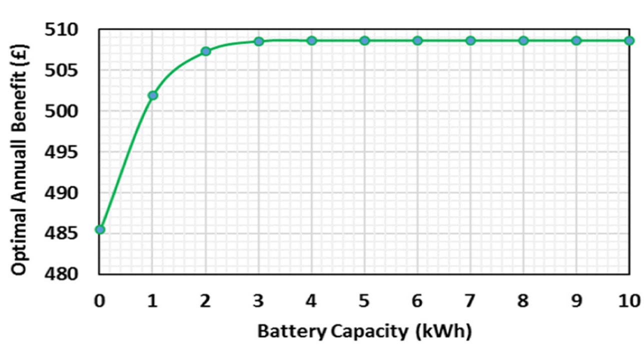

Fig. 17. Impact of varying battery capacity on the objective function for case study 2.

Table 2
Revenue for PV owner in case study 1 and 2.

Study Case	OF (£)
Case Study 1	314.04
Case Study 2	482.28
Case Study 3	507.28

Table 3
Annual energy from PV and grid.

Case study	Total PV energy (kWh)	Total grid energy import (kWh)
2	3418	1099
3	3418	1107

5.5. Annual energy from PV and grid for case studies 2 and 3

Table 3 summarises the annual energy from PV and grid for case study 2 (with economy 7 tariff) and case study 3 (with wholesale electricity tariff).

It could be seen that the same PV energy is yielded for case studies 2 and 3 because the PV generation is same for both scenarios and is modelled as a parameter in the optimisation model. The total PV capacity for both scenarios is 3.36 kW.

5.6. Discussion of results

The simulation of the developed optimisation model with wholesale electricity tariff shows an interesting perspective of the management of battery energy flows which could be deployed for existing PV systems benefiting from FiT incentives. Figs. 14, 15, 16 provide insights for potential aggregators acting on behalf of a group of buildings with PV systems on how they maximise revenue streams by deploying battery storage. It also shows how to optimise system operation in periods of low, high and even negative wholesale tariff periods. (example Figs. 14–16).

The sensitivity analysis procedure can be used by PV – battery system designers to carry "what if analysis" of different parameters of the optimisation model. For example, the battery storage capacity that will maximise revenue streams for an existing residential PV generation systems under time-varying electricity tariffs and FiT.

6. Case studies for the new PV system

The PV generation system capacity (kW) was modelled as a decision variable and simulated in DER-CAM with the datasets for electricity demand and solar irradiance using the location (longitude and latitude) of the PV system described in section 5.

Three scenarios are run in DER-CAM, all with the economy 7 time of use tariff (see Fig. 4):

- Case Study 1: Reference, no PV and battery system.
- Case Study 2: PV + FiT + Battery storage at a unit cost of $990/kWh (£683/kWh) [81]. Both PV and Battery are modelled as decision variables.
- Case Study 3: PV + FiT + Battery storage with a sensitivity analysis on the unit costs of battery storage ($/kWh) in case study 3. Again, both PV and Battery are modelled as decision variables.

6.1. Case study 1 results

Case study 1 serves as a reference case (business as usual) with no onsite PV and all electricity demand is supplied from the utility grid.

6.2. Case study 2 results

In this case study, both the PV and battery storage capacities are decision variables in the DER-CAM optimisation model. After running the model, the output from DER-CAM includes the optimal capacities of distributed energy resources (PV and battery storage in this paper). The optimal PV capacity decided by the optimisation model for case study 1 is 3 kW, and no battery storage was invested due to the high cost of the battery storage (see Table 4). The optimal power profiles for case study 2 with no battery storage adopted are shown in Fig. 18. With no battery storage and higher PV generation compared to electricity demand, the PV satisfies onsite demand and the excess PV is sold to the grid at the cheap PV FiT export tariff (4.64 p/kWh). Figs. 19 and 20 respectively shows the grid electricity purchased for the three-day types (week, peak and weekends) in DER-CAM during the period of winter and summer. The peak grid electricity purchase in both cases is greater than the weekdays and weekend days. This is because the peak day is a day in each month of the year with highest electricity demand.

It is also observed that the grid purchase is lower in summer compared to winter because of higher onsite PV generation in the summer months. The grid purchase patterns of weekdays and weekends also show similar patterns except in the peak electricity demand period (20:00–21:00) when the weekend grid electricity purchase is slightly higher than that of weekdays.

Table 4
Results for case studies 1, 2 and 3.

Scenario	Annual electricity costs (£)	Optimised OF (£)	PV capacity (kW)	Battery power (kW)	Battery capacity (kWh)
S1	328.21	328.21	0	0	0
S2	161.76	−228.34	3	0	0
S3	100.9194	−239.14779	3	1.27	2

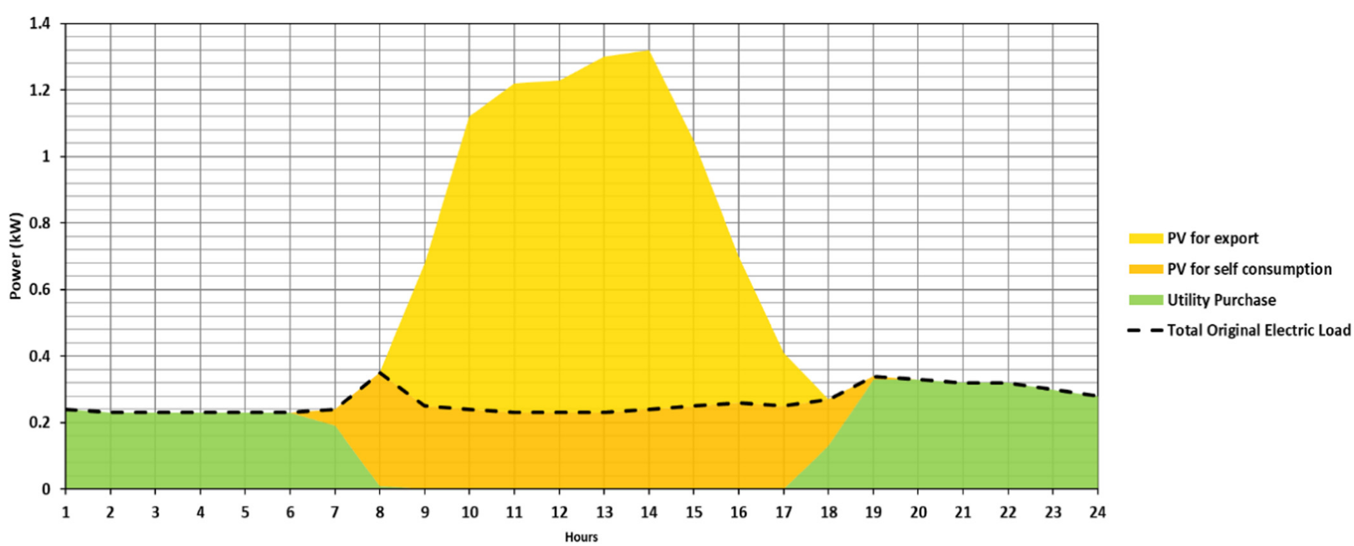

Fig. 18. Power profiles for a typical day in summer.

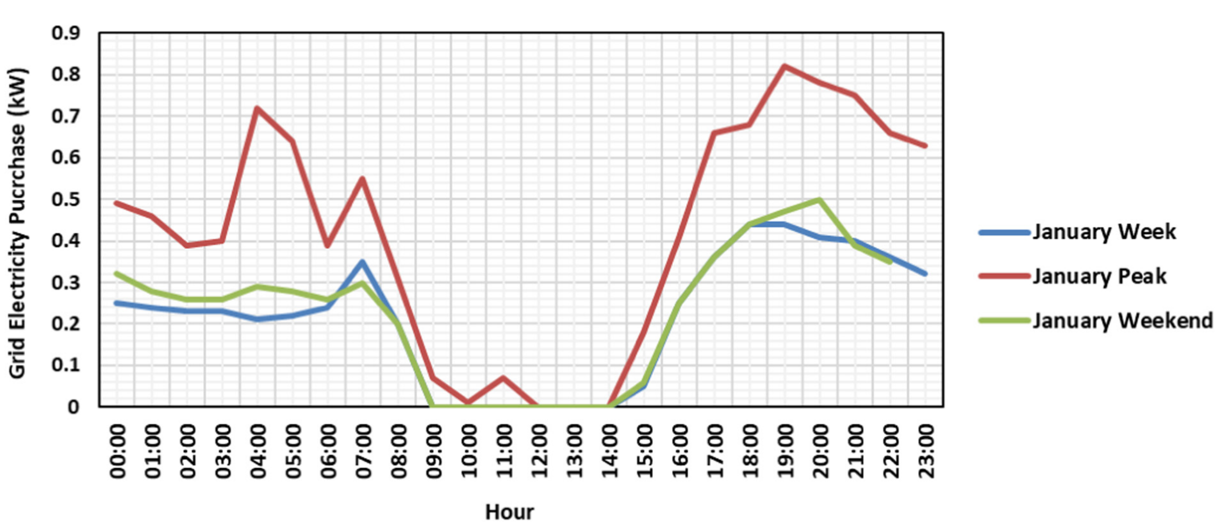

Fig. 19. Grid electricity purchase for Week, Peak and Weekend days (Winter).

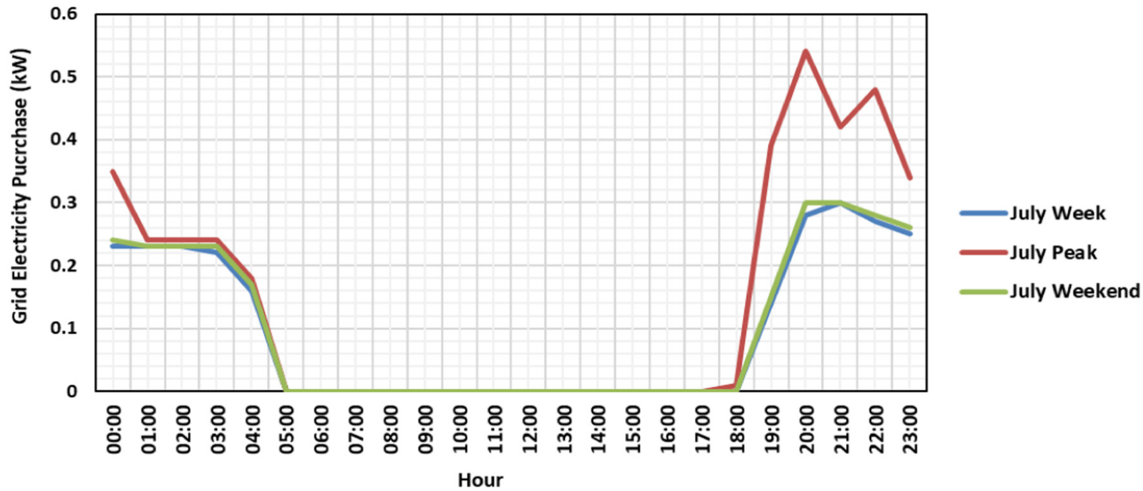

Fig. 20. Grid electricity purchase for Week, Peak and Weekend days (Summer).

6.3. Case study 3 results

In this case study, the battery storage unit cost is varied until battery storage is adopted in DER-CAM. At the unit cost of £138/kWh, battery storage of 2 kWh was adopted (see Table 4). Fig. 21 shows the optimal power profiles with the battery storage adopted at a unit cost of £138/kWh). It could be seen that the battery discharges at periods of peak electricity demand (high economy 7 tariff rate) after charging shown by the state of charge in the secondary axis of Fig. 21. The amount of PV for self-consumption increased compared to the case when no battery storage was adopted (see Fig. 18).

In Figs. 22 and 23, the grid electricity profiles for winter and summer are respectively presented. Both are presented for the typical DER-CAM types (week, peak and weekend) days.

It could be observed that the grid purchase in the winter peaks the hours 04:00–06:00 to take advantage of the low economy 7 tariff of about 6 p/kWh to import electricity. After that period, the grid electricity purchase is lower compared to the case when no battery storage was adopted by the optimisation mode (see Figs. 19 and 20). It is also observed that summer case with battery storage adopted (see Fig. 23) extend the one hour more of zero grid electricity purchase when compared with the summer case with no battery storage.

6.4. Annual grid purchase and PV summary for all case studies

Fig. 24 presents the annual energy from PV and grid. It is observed with no PV installed the annual grid electricity import is about 2508 kWh which reduces to 1392 kWh with PV installed and a further reduction to 1066 kWh when battery storage was adopted.

6.5. Objective function summary

Case studies 2 and 3 were simulated to evaluate the minimum unit cost of storage that will make economically viable the battery storage for the PV modelled as a new system.

Table 4 shows the summary results for case studies 1, 2 and 3. Case study 1 shows that the system total cost of meeting electricity demand with no PV is about £328.

With case study 2, the modification to add FiT tariff is implemented in DER-CAM and the objective function becomes negative meaning that the amount earned from generation and export tariff is greater than the cost of electricity imported from the grid to meet the onsite electricity demand.

Table 4 also presents the case study where battery storage is considered. It is observed that at the battery unit cost of £683/kWh, the battery storage was not adopted by the optimisation

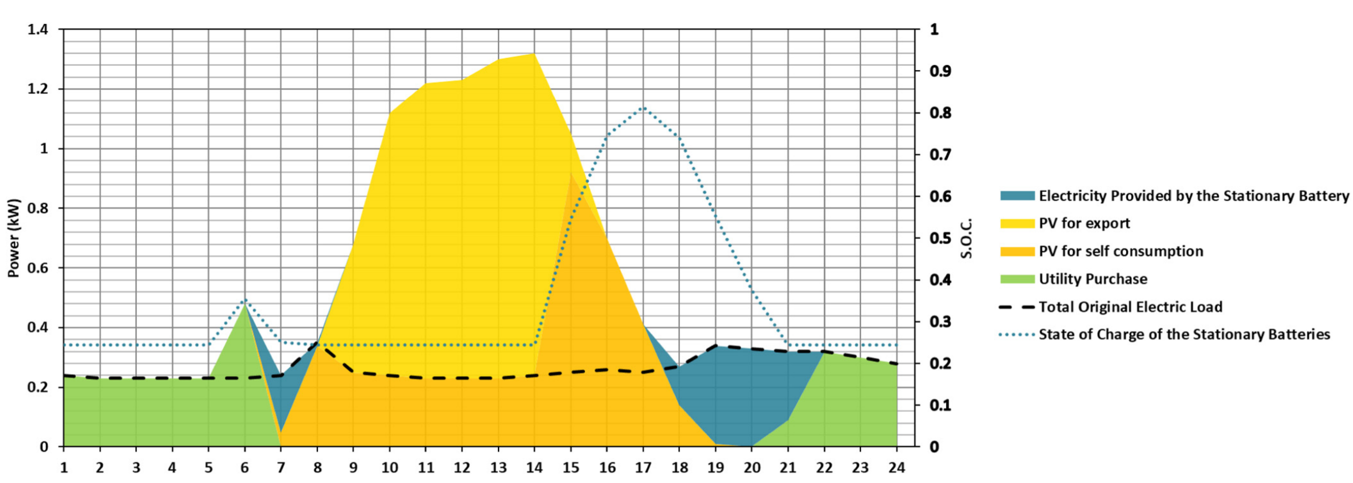

Fig. 21. Power profiles for case study 3.

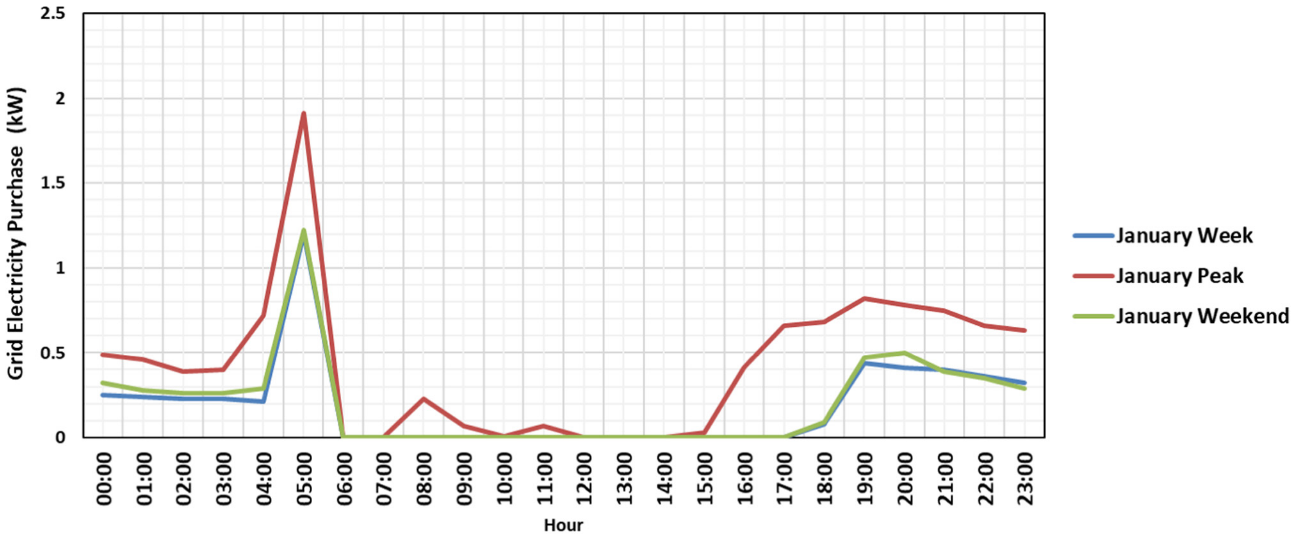

Fig. 22. Grid electricity purchase for Week, Peak and Weekend days (winter).

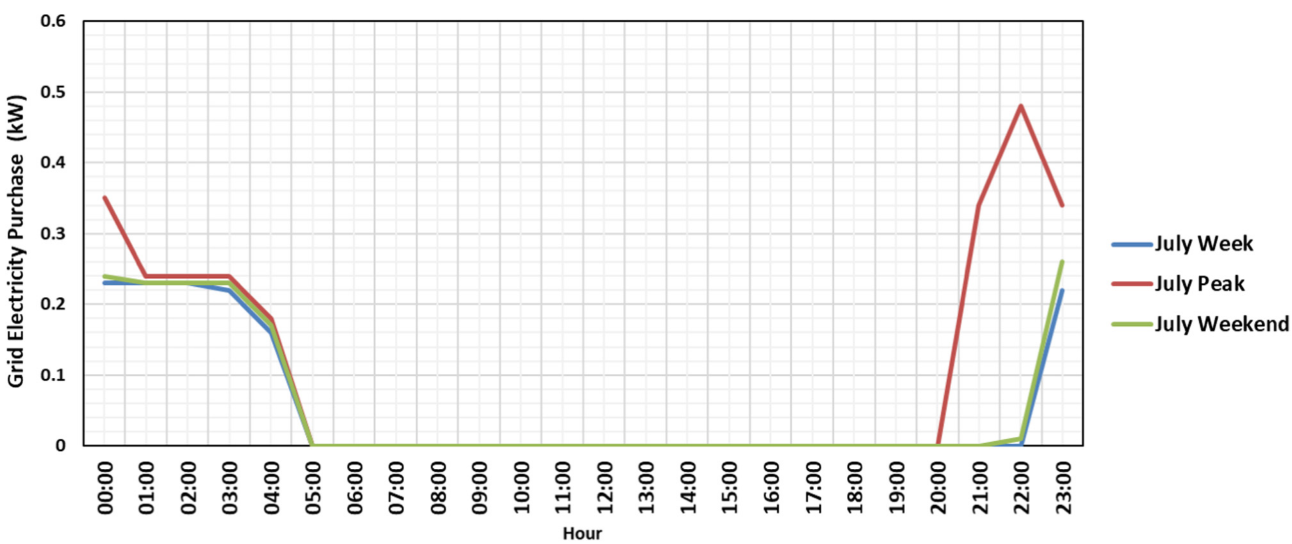

Fig. 23. Grid electricity purchase for Week, Peak and Weekend days (summer).

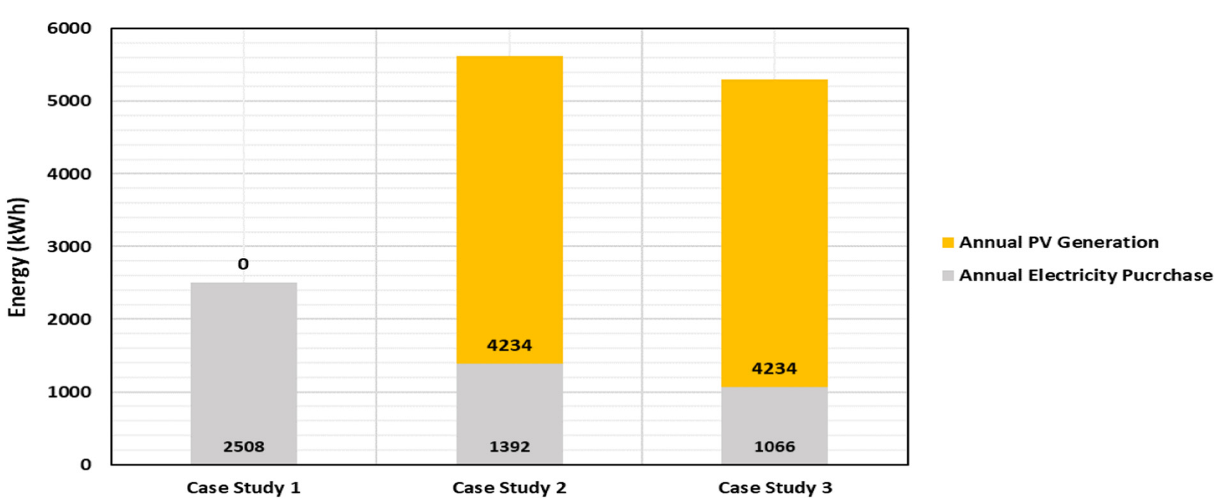

Fig. 24. Annual PV and Grid Energy for three case studies.

model in DER-CAM, meaning that at such unit costs, the battery storage does not make economic sense for the new PV system.

However, the optimisation in DER-CAM only adopts battery storage and PV generation system when the unit cost of battery storage reaches £138/kWh (case study 3). A 2 kWh battery is installed showing that battery unit cost should drop to £138/kWh or lesser for a combination of PV and battery storage system to be economically viable under a time-varying electricity tariff FiT incentive.

7. Discussion

Deploying battery storage (Maximisation of FiT revenue streams) for existing/new PV systems under FiT incentive systems and time-varying electricity tariffs are becoming attractive due to the significant difference between retail tariff and FiT export tariff. This difference between electricity buying and selling is noticeable in net metering and FiT schemes around the world (see [76]). However, previously reviewed literature did not find a suitable optimisation formulation to evaluate the value of battery storage for the existing and new PV system benefiting from FiT incentive and under time-varying electricity tariff rates.

This paper examined the value of battery storage with different electricity tariff structures on revenue streams for an existing PV system under FiT incentives.

In a second step, the impact of the unit cost of battery storage on the adoption of the battery storage system for a new PV system was investigated in the DER-CAM optimisation platform. The DER-CAM model has been previously used to assess net metering incentives on the adoption of distributed energy resources, in this paper the formulation in DER-CAM was modified to include a FiT scheme that rewards generation and export from a PV system.

However, if electricity customers with onsite distributed energy systems are to optimise their systems with battery storage based on FiT and time-varying electricity tariff incentives, what will be the impact of their connection to a local distribution network? This question was not addressed in this paper and be used as a further direction for future work.

8. Conclusion

In this paper, an optimisation model was developed to optimise FiT revenue streams for an existing and new PV generation system coupled with battery storage. For the existing PV system, the optimisation model was simulated for a complete year with real half-hourly PV generation profiles. The impact of the unit cost of storage (price/kWh) on the adoption of the battery storage system for a new PV system was also investigated in the DER-CAM optimisation platform.

The conclusions are:

(1) In the case of the PV system with no battery storage, PV generation is used for self-consumption and any generation excess is sold at 4.64p/kWh. However, with economy 7 and wholesale electricity tariff, the battery charges from the grid when the electricity tariffs are low or negative and discharge at high electricity tariff periods. Also, it was found that the battery prefers to charge when the PV generation is at its maximum and switches to charge using grid electricity when the PV generation drops and wholesale electricity tariff is low.

(2) It was found that the new PV system sized in DER-CAM has higher total annual energy production of about 4234 kWh compared with to 3418 kWh with real half-hourly PV generation profiles. Simulation models with irradiance data can be optimistic and therefore the use of real PV generation data is recommended for evaluating benefit storage for real existing PV systems benefiting from FiT incentives.

(3) The sensitivity analysis for evaluating the impact of battery storage capacity on objective function shows that with the wholesale sale electricity tariff, the battery capacity could be increased to 3 kWh for a marginal increase in revenue.

(4) Multi-tier based time of use electricity tariffs can offer similar revenue streams compared to wholesale electricity tariffs. This can be seen in the objective function values for the existing PV system, £482 for the economy 7 tariff and £507 in the case study with wholesale electricity tariff. This represents a 5% increase (not a significant increase) in the objective function when the wholesale tariff was used instead of the economy 7 in the case of the existing PV system. Also, battery adoption for the PV simulated as a new system will only be economically viable when battery unit cost drops to £138/kWh.

Acknowledgement

Abubakar Sani Hassan would like to acknowledge the PhD scholarship he received from the Petroleum Technology Development Fund, Nigeria. He would also want to acknowledge the support of Dr Michael Stadler and Dr Salman Mashayekh of the Grid Integration Group, Lawrence Berkeley National Laboratory and Tim Schittekatte, of the Florence School of Regulation (Energy & Climate). The authors would also like to acknowledge the EPSRC project "Ebbs and Flows of Energy Systems" (EP/M507131/1) for supporting part of this work.

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